REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
05-07-2017	Final Report	1-Sep-2013 - 31-Aug-2016

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Final Report: Locomotor Stability in a Model Swimmer: Coupling Fluid Dynamics, Neurophysiology and Muscle Mechanics	W911NF-13-1-0289
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
	611102

6. AUTHORS	5d. PROJECT NUMBER
Lisa Fauci, Eric Tytell	
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
Tulane University 1430 Tulane Avenue, EP 15 New Orleans, LA 70112 -2632	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
	62252-MA.5

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

We use multiscale modeling and computational fluid dynamics to examine the stability of a swimming organism in the face of perturbations, with and without sensory feedback. We focus on the lamprey, the most basal living vertebrate, and hence a model organism for studying the neural control of locomotion. We investigate how the coupling among forces due to passive tissue properties, active muscular forces and the forces from the external fluid environment contribute to the dynamics and stability of swimming.   Using our integrative computational model, we can impose external perturbations to the fluid environment as well as internal perturbations to the neural

15. SUBJECT TERMS
fluid dynamics, swimming stability

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Lisa Fauci
UU	UU	UU	UU		19b. TELEPHONE NUMBER
					504-862-3431

RPPR
as of 25-Aug-2017

Agency Code:

Proposal Number: **Agreement Number:**

Organization:
Address: , ,
Country:
DUNS Number: EIN:
Report Date: Date Received:
 for Period Beginning and Ending
Title:
Begin Performance Period: **End Performance Period:**
Report Term: -
Submitted By: Email:
                                                    Phone:

Distribution Statement: -
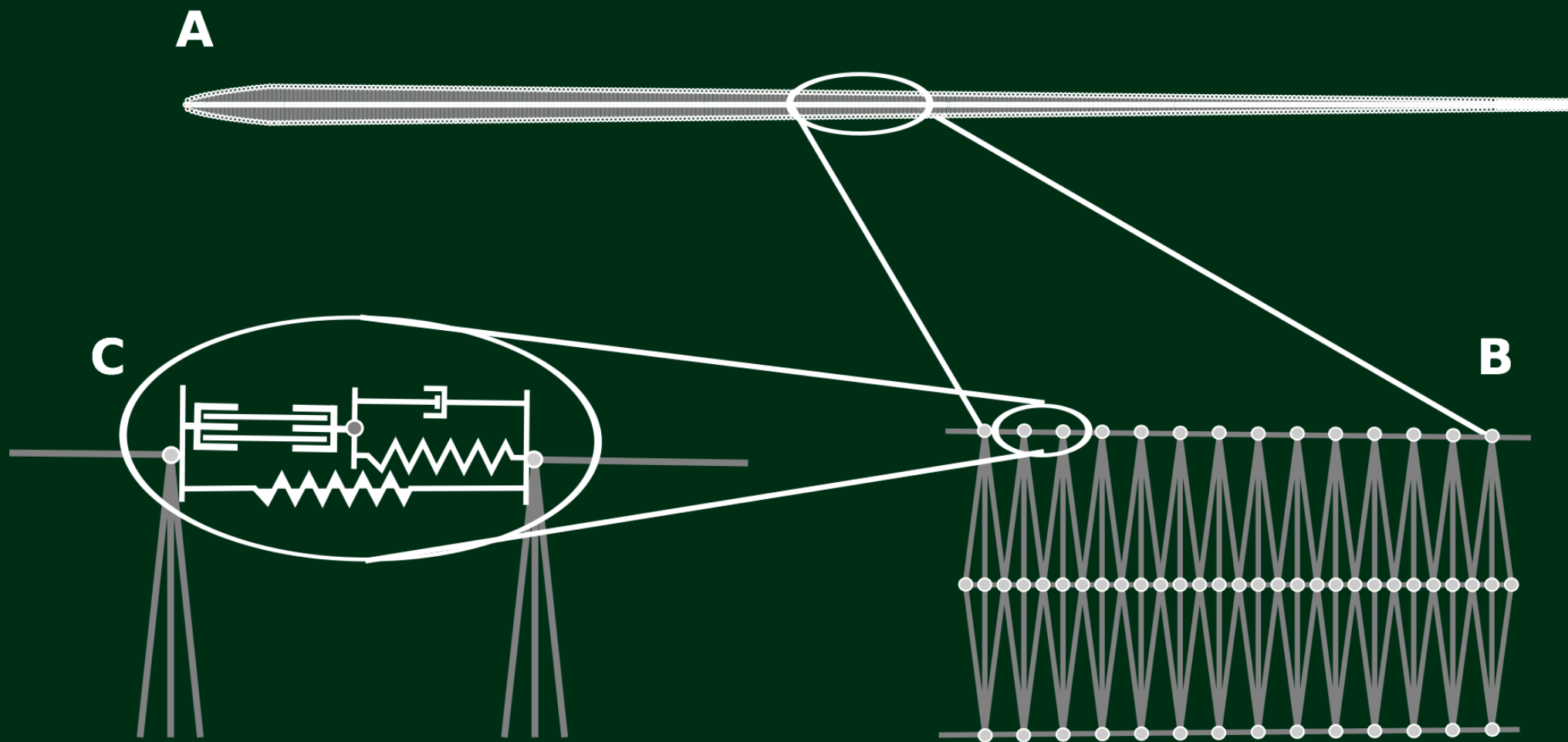
STEM Degrees: **STEM Participants:**

Major Goals:

Accomplishments:

Training Opportunities:

Results Dissemination:

Plans Next Period:

Honors and Awards:

Protocol Activity Status:

Technology Transfer:

This is a schematic of the computational body. (A) The initial configuration of the material points. (B) The gray lines show elastic springs which resist deformation. (C) Inset that shows the position of the muscle segments.

Hamlet, Fauci, Tytell, J.Theo. Bio 2015

A representative plot of bursting signals at different positions on the lamprey body. The "R" and "L" on the left side indicates right and left, respectively. The numbers are the segment number, labeled from head to tail.
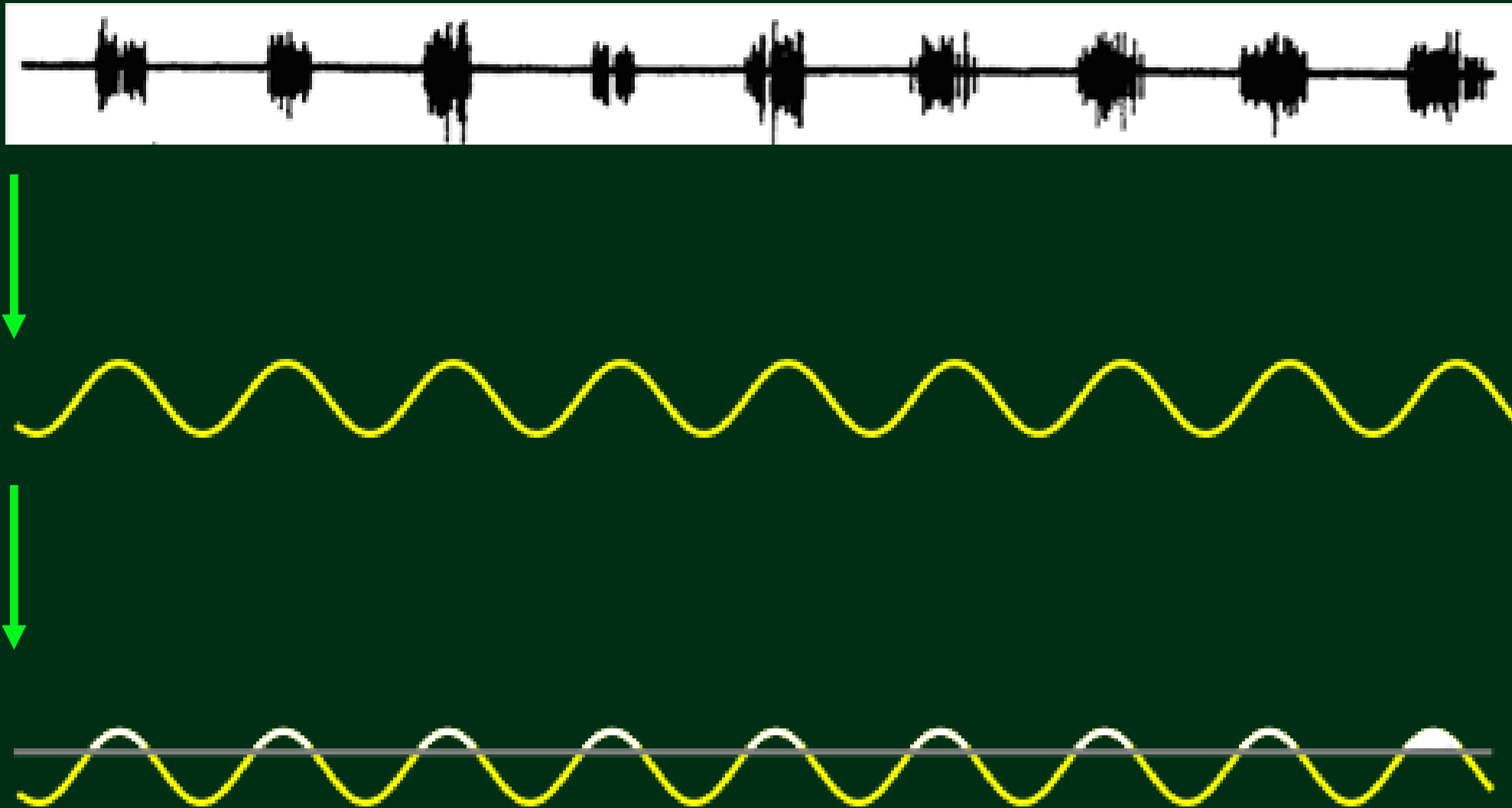
Cohen, Holmes, Rand, J. Math Biol. 1982

The signals are periodic.

Cohen, Holmes, Rand, J. Math Biol. 1982

From head to tail there is a phase lag on each side.

Cohen, Holmes, Rand, J. Math Biol. 1982

On a given segment, the signals are in antiphase.

Cohen, Holmes, Rand, J. Math Biol. 1982

# Periodic nature of CPG motivates modeling by an oscillator

Using one signal as a representative example, we define an oscillator described by its phase that generates a signal. Then a threshold is applied based on experimental data.
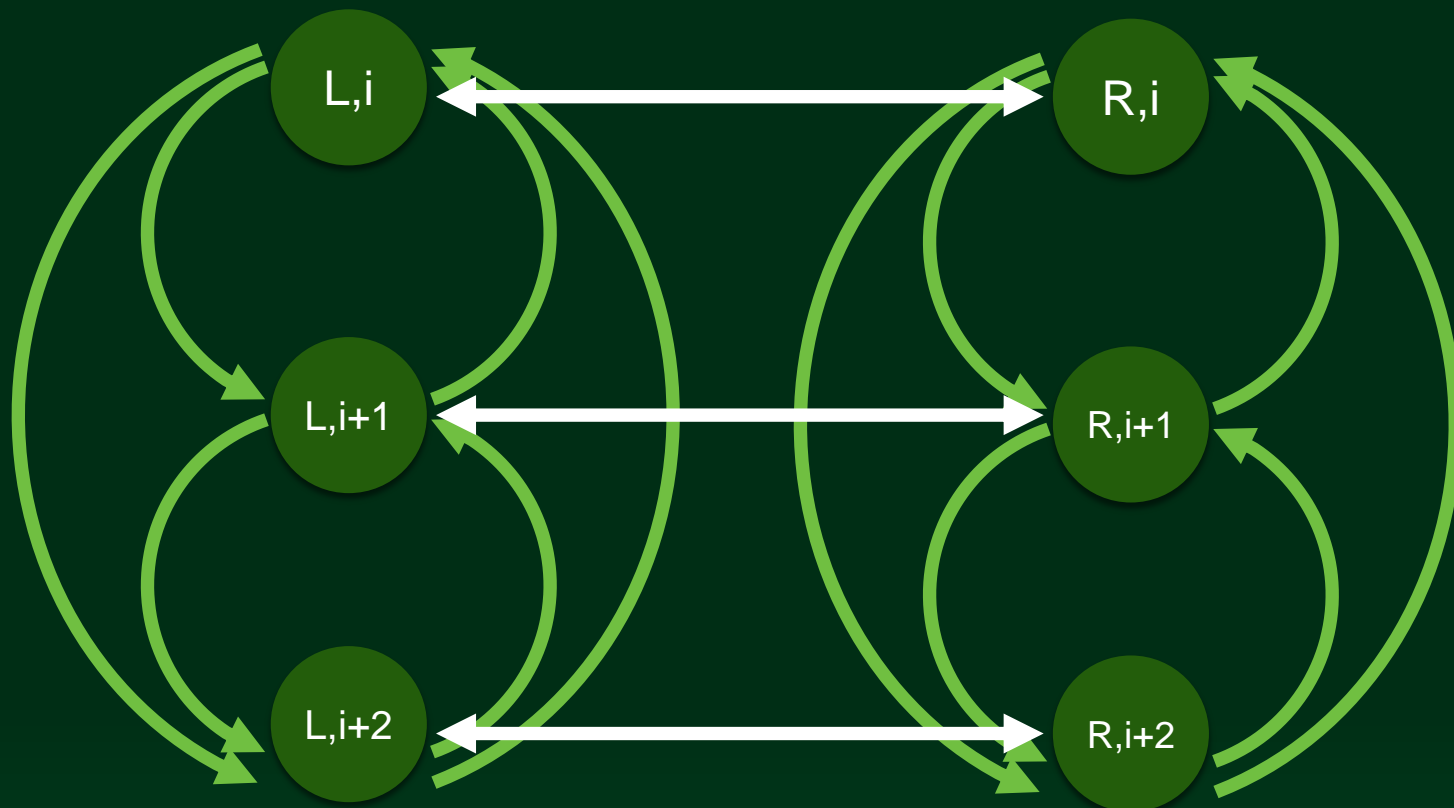
Oscillators generate a signal
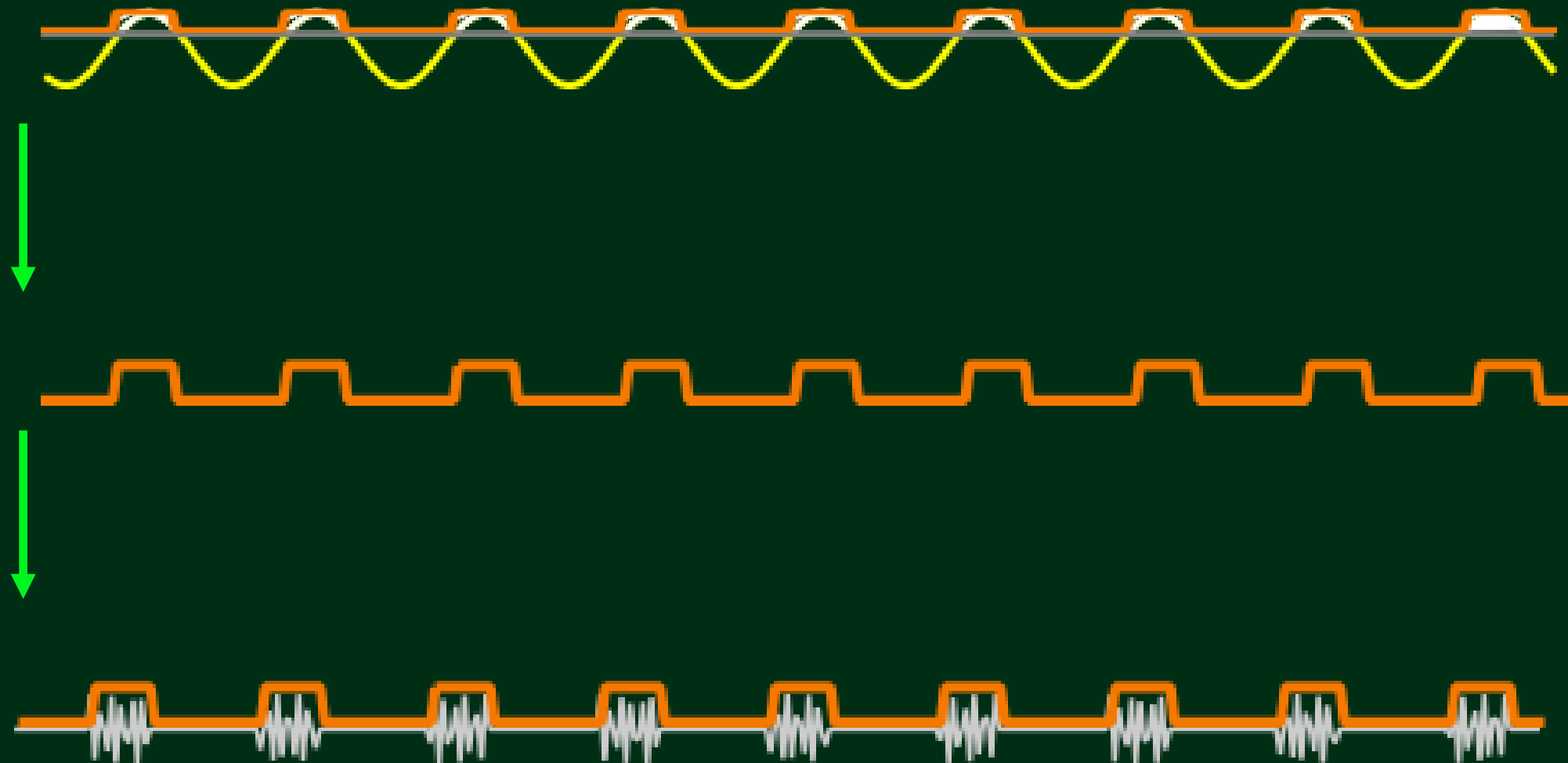
Applying the threshold to define "active" and "inactive" and coarsely approximate the observed experimental signal.
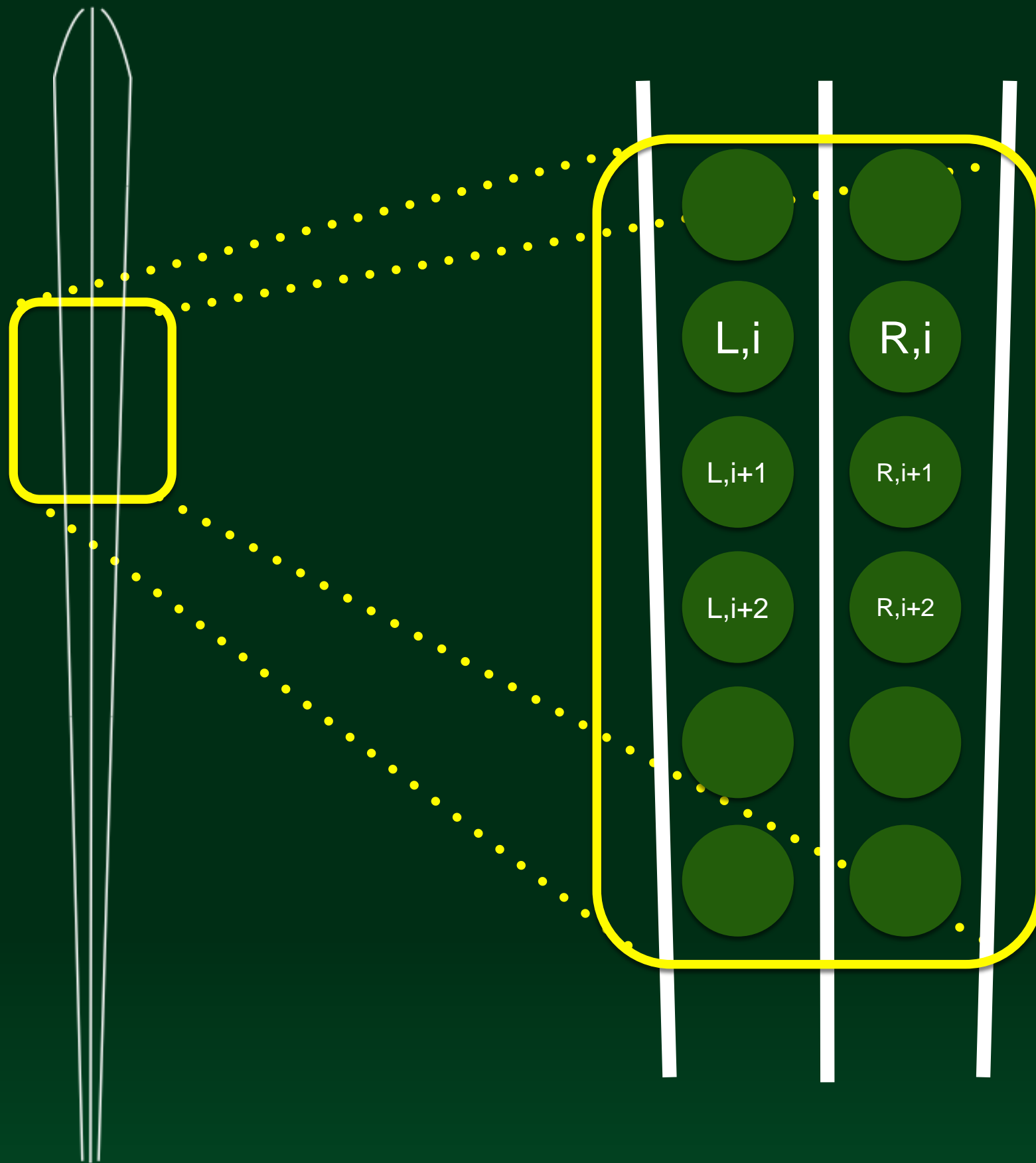
Oscillators are assigned one-to-one to the muscle segments and coupled according to experimental guidance.

$$\dot{\theta}_{k,i} = \omega + \alpha_c \sin\left(2\pi\left(\theta_{k*,i} - \theta_{k,i} + \varphi_s\right)\right)$$

$$+ \sum_{j=1}^{n} \alpha_{i-j} \sin\left(2\pi\left(\theta_{k,j} - \theta_{k,i} - \psi_{i-j}\right)\right)$$
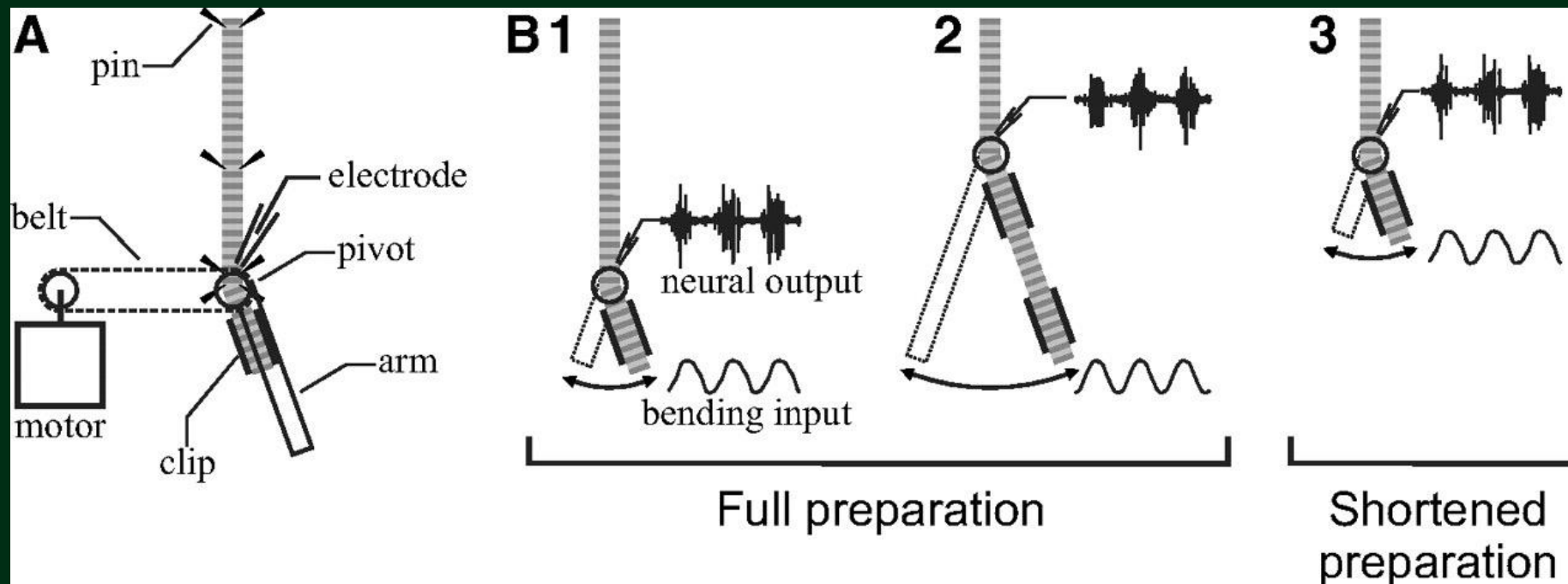

The oscillators are coupled all-to-all one each side (green arrows showing example) and across a segment (white arrows show examples). For each oscillator ω represents the natural frequency, θ is the phase, Φ is the phase lag down the body, ψ is the phase lag across a segment.
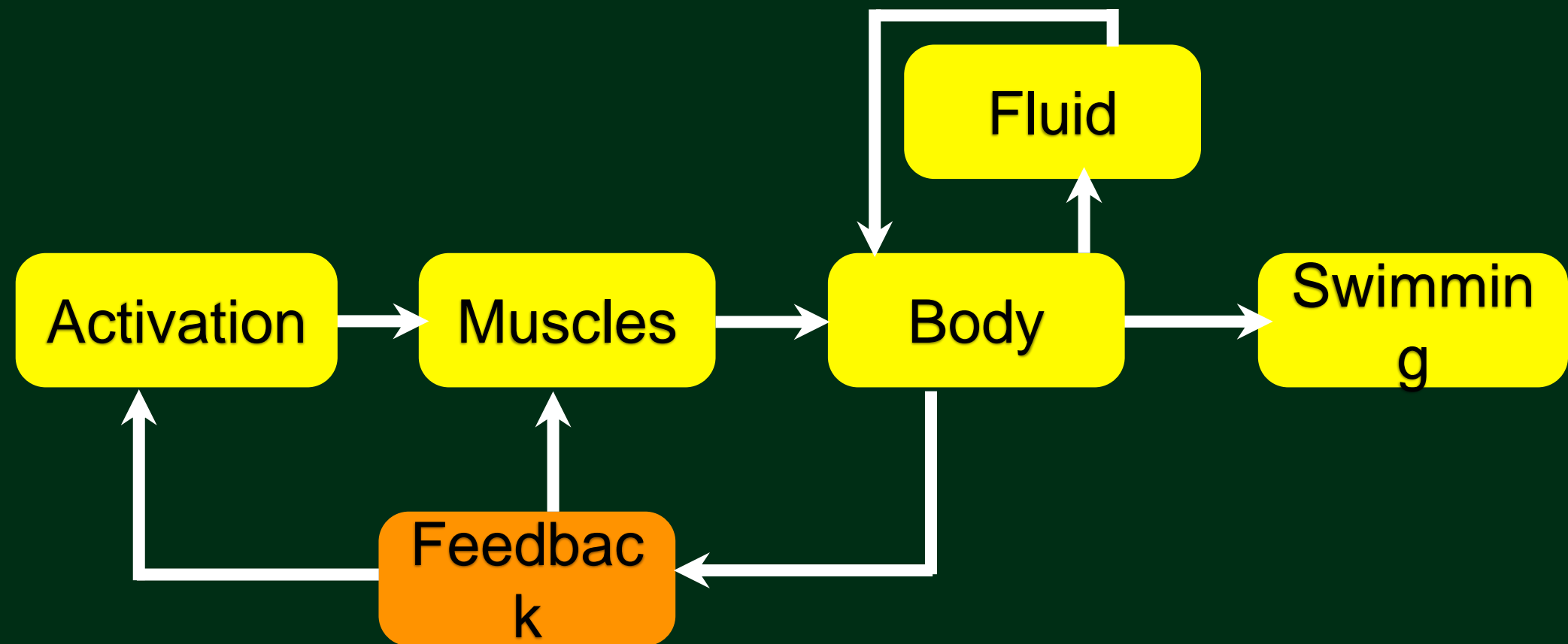
Feedback diagram. Feedback added though curvature sensing.
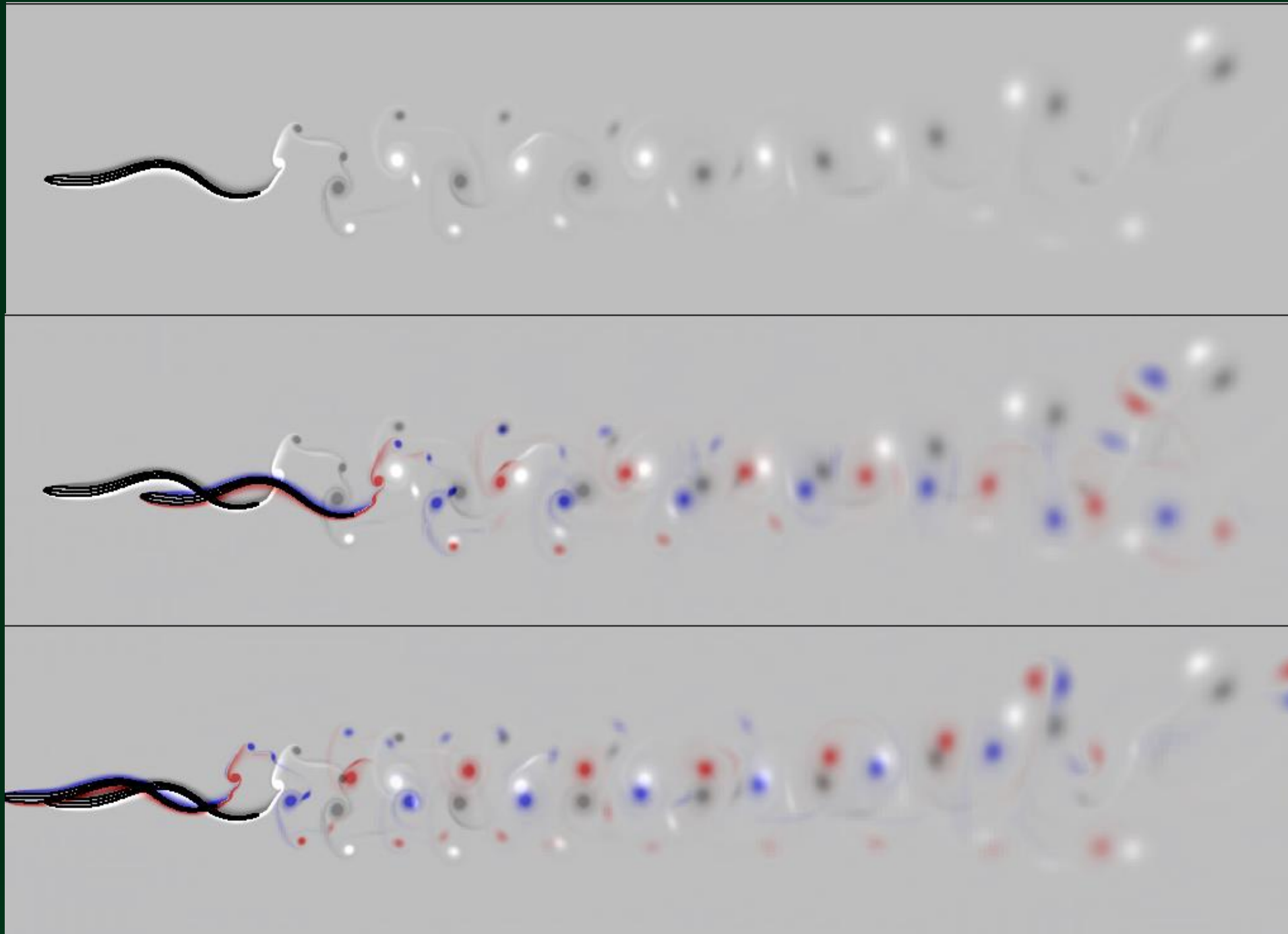
Edge cells and sensory feedback

Schematic of Eric's experimental set up.

# Connect sensory feedback to oscillators

$$\dot{\theta}_{k,i} = \omega + \alpha_c \sin\left(2\pi\left(\theta_{k*,i} - \theta_{k,i} + \varphi_s\right)\right)$$

$$+ \sum_{j=1}^{n} \alpha_{i-j} \sin\left(2\pi\left(\theta_{k,j} - \theta_{k,i} - \psi_{i-j}\right)\right)$$

$$+ \boxed{\eta_{k,i}\left|\bar{\kappa}\right|} \longleftarrow \quad \eta_{k,i}\left|\kappa\right| = g\left|\kappa\right|$$

Propose forms of functional feedback. The one shown here will advance the activation wave if the gain (g) is positive proportional to the curvature (κ), and will slow the activation wave if the gain is negative.
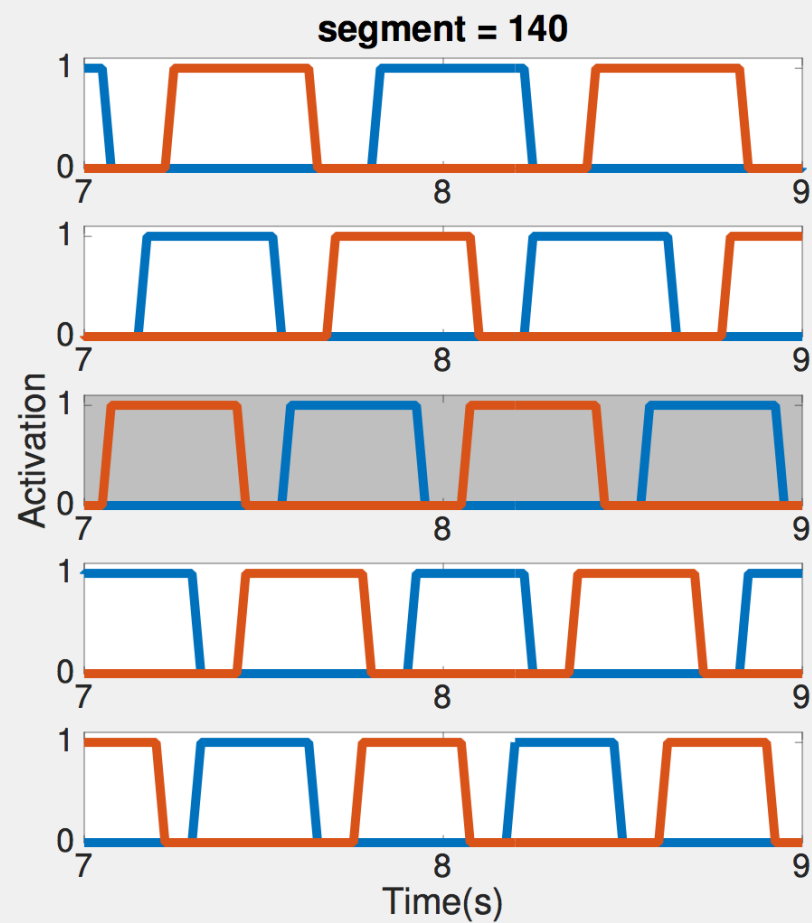
Top: No feedback
Middle: Negative gain
Bottom: Positive gain

Changing the feedback term changes the behavior of the swimming lamprey (see the next slides)
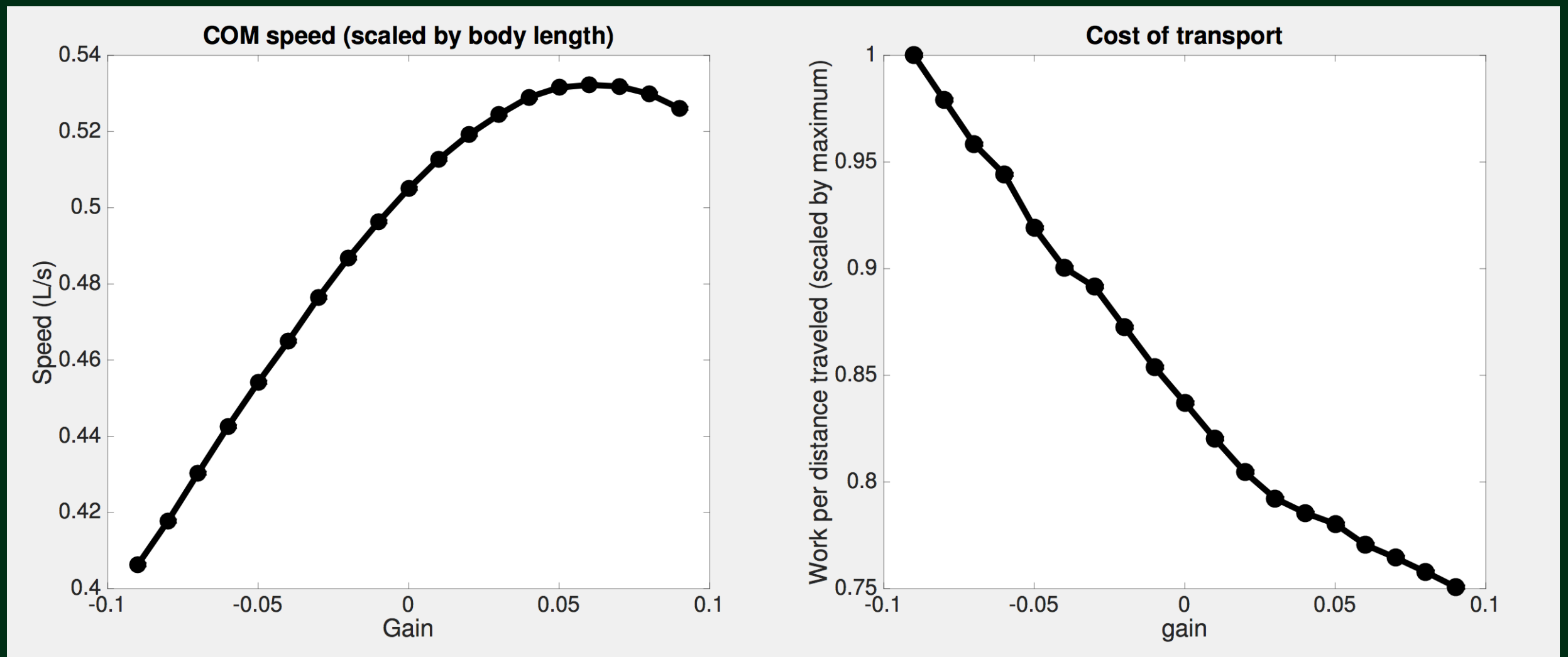
Left plot shows the swimming speed at the center of mass of the swimmer in each simulation in (L/s) where L=body length). Right plot shows the work per unit distance (cost of transport) scaled by the maximum value.
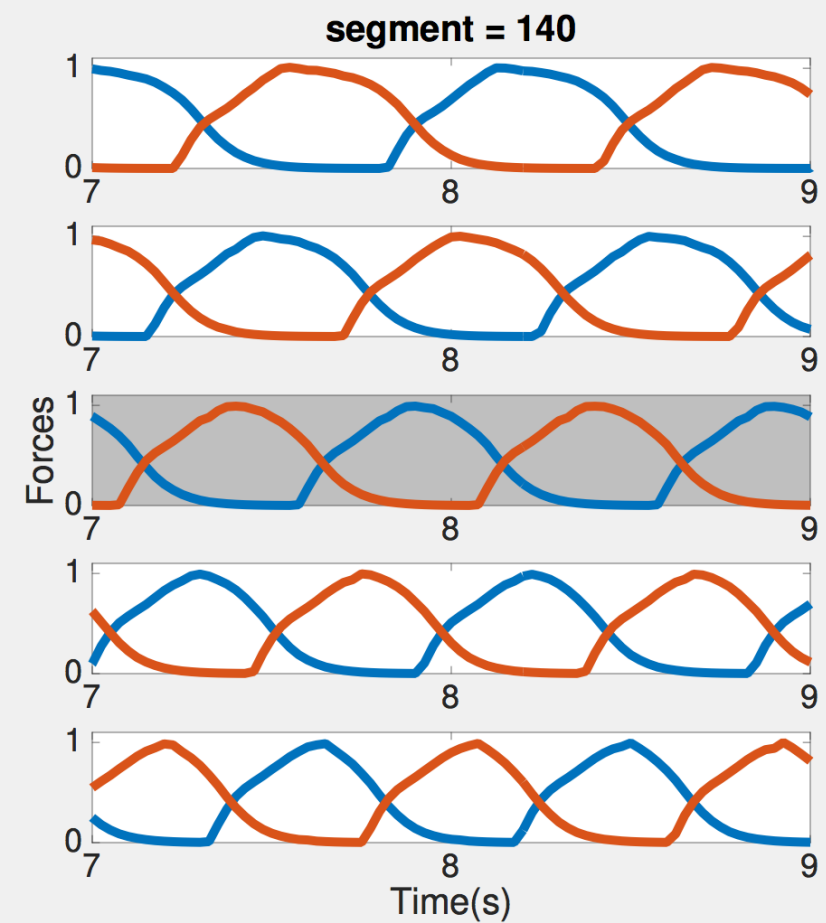
Plots to illustrate the effect of the feedback term (g|κ|), left plot shows that at a given segment, the feedback increases the tail beat frequency as the gain increases. The right plot shows that the area under the force curve during each cycle is decreased, reducing the achieved amplitude.